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Research Article

Narrow-Band 1D Photonic Crystal Based Omni-Directional Mirror at 1550nm for Optical Fiber Communication

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Abstract: Omni-directional reflection (ODR) property of one-dimensional photonic crystal (PC) structures consisting of alternate layers of Germanium (Ge), and zinc sulfide (ZnS) has been investigated. The existence of total Omni-directional reflection band gap in 1D-PC is predicted theoretically. Reflectivity of one dimensional periodic structure for TE and TM-modes at deferent angles of incidence has been calculated by using Transfer Matrix Method (TMM). It is found that the mirror designed with these materials has a ODR range which covers the window of 1550 nm used in optical communications.

Keywords: Photonic crystal, ODR, Optical filter, TMM, multilayered mirror.

INTRODUCTION

In general, photonic crystals (PCs) may be considered as a new class of optical materials[1-4]. These materials are based on the interaction between an optical field and materials exhibiting periodicity on the scale of wave length. The main feature of photonic crystals is that they can prohibit the propagation of electromagnetic waves within a certain frequency range called photonic band gap (PBG). The materials exhibiting PBG have many potential applications in optoelectronics and optical communication. For the optical range within which the main application is expected, most of the experimental effort has been concentrated on two dimensional and three dimensional photonic crystals. However, we shall concentrate on one dimensional PC structures as such structures can be realized easily and compatible with already established semiconductor technology.

One dimensional photonic crystal is attractive since their fabrication is more feasible at any wavelength scale and their analytical and numerical calculations are simpler. PCs are beginning to have a profound effect on the development of nanoscale devices because they can significantly enhance the interactions between light and matter. It has been shown that one dimensional photonic crystals can totally reflect arbitrarily polarized, transverse-electric (TE) and transverse-magnetic (TM), lights i.e. these crystals exhibit the property of Omni-directional reflection [3-5, 18]. The total reflection band that occurs in any direction for TE and TM polarization can be exploited in the design of omni-directional reflection mirror.

Mirrors are of two basic varieties, a metallic mirror or Omni- directional reflector and a dielectric Bragg mirror. One dimensional photonic crystal is designed as Bragg mirror[6, 10]. In particular, a large number of one-dimensional photonic crystals were designed for their applications in the infrared wavelength ranges. Several research groups have reported that easy to fabricate Bragg mirrors which are low loss Omni-directional reflector [11–15, 20-22]. Fink et al[3]. and Winn et al[16]. first reported independently that the one dimensional dielectric lattice displays total omnidirection reflection for incident light under certain conditions. Also, Yao[17] studied a wide range of realistic fabrication parameters for the formation of Omni-directional photonic band gaps (PBGs) in one-dimensional photonic crystals, theoretically as well as experimentally.

In this paper, we study the Omni-directional reflection (ODR) in one-dimensional photonic crystal (PC) structures consisting of alternate layers of Germanium (Ge), and zinc sulfide (ZnS). The theoretical analysis is based on the transfer matrix method. For the optical properties of Ge, the data used from 0.18µm- 11µm are those of Lapote et al[19]. For ZnS, the data used for the range 0.36µm- 1.55µm are taken from DeVore et al[23].

THEORY

Consider electromagnetic wave propagation in one-dimensional (1D) system that consists of alternate layers of dielectric materials with different refractive indices. We consider the system to be isotropic and nonmagnetic. The refractive index profile of the PBG is given by

$$n_x = \begin{cases} n_1, & 0 < x < d_1 \\ n_2, & 0 < x < d_2 \end{cases} \qquad with\, n(x) = n(x+d) \qquad (1)$$

Where d_1 and d_2 are the thicknesses of the layers and $d = d_1 + d_2$ is the lattice period. Here the x-axis is taken along the direction perpendicular to the layers. To calculate the reflectivity of this PBG structure, we have used transfer matrix method (TMM).

For a plane wave propagating in the z-direction, the electric field can be written as

$$E = E(x).exp[i(\omega t - \beta x)] \qquad (2)$$

Where the x-component of the wave is vector and is the angular frequency.

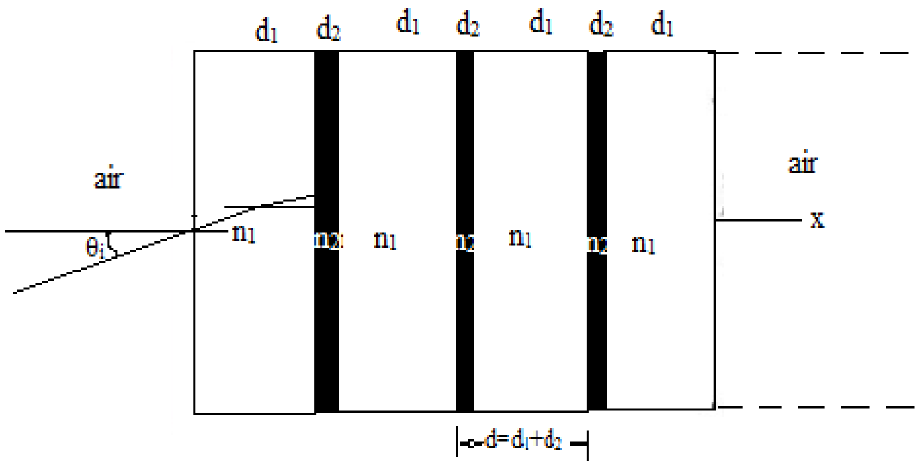

Fig.1: Periodic variation of one-dimensional photonic band gap structure.

A periodic arrangement of a multilayer films with refractive indices n_1 and n_2 and thickness d_1 and d_2 respectively is shown in **Fig.1**. The electric field distribution within each layer can be expressed as the sum of an incident plane wave and a reflected plane wave. The incident light can be either transverse electric (TE) or transverse magnetic (TM) mode. The amplitudes of the fields in the first layer of N^{th} unit cell and $(N-1)^{th}$ unit cell are related by a matrix,

Where, – – ,

– – ,

– – ,

– – …. (4)

are the coefficients of the right and left hand side propagating waves in the first layer of the N^{th} unit cell. Considering the structure of N period of layers with alternate refractive indices n_1 and n_2 having thicknesses d_1 and d_2. The coefficients of propagating states in right and left side of the multilayer structures are calculated by the multiplying transfer matrices of each cell.

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = (M)_1 \times (M)_2 \times (M)_3 \dots \dots \dots \dots (M)_N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \qquad (5)$$

The reflectance coefficient is given by,

$$r_N = \left(\frac{b_0}{a_0}\right)_{b_{N=0}} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \qquad (6)$$

$$\therefore \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N = \begin{pmatrix} AU_{N-1} - U_{N-2} & B_{N-1} \\ C_{N-1} & DU_{N-1} - U_{N-2} \end{pmatrix}$$

$$where, \qquad U_N = \frac{\sin{(N+1)Kd}}{sinKd}$$

The reflectance is obtained by taking absolute value of the reflectance coefficient,

$$R = (|r_N|)^2 = \frac{|C|^2}{|C|^2 + \left(\frac{\sin Kd}{sinNKd}\right)^2} \qquad (7)$$

RESULTS AND DISCUSSION

For our calculations we take Ge/ZnS dielectric material with low and high refractive index. The refractive index of Ge is $n_l = 4.23$ and ZnS is $n_2 = 2.27$. Taking thickness of the each layer same $d_1 = 0.9d$, $d_2 = 0.1d$ and $d = d_1 + d_2 = 1170\,nm$. Applying transfer matrix method, we get relations for dispersion characteristics and reflectance. We plotted reflectance of the structure with wavelength for various angles of incidence. **Fig. 2 and Fig. 3** show the reflectance of the structure for different angles of incidence, namely, 0^0, 15^0,30^0, 45^0,60^0, 75^0 and 89^0 for TE and TM mode respectively and the ODR range for angles of incidence from 0^0 to 89^0 is shown in **Fig.4 & Fig.5.**

The reflectance spectra of proposed one dimensional PBG structure is shown in figure 6 & figure 7 for TE and TM mode of polarization respectively. These spectra are plotted in terms of wavelength and for incident angle θ_i.

From the plots of reflection spectra for different angles of incidence, 100 percent reflection ranges for different angles of incidence are tabulated in **Table-1.** It is clear from **Table-1** that the reflectance-range for TE mode is 1540-1620 nm at normal incidence; at the angle of 15^0 the range is 1536-1617 nm; at the angle of 30^0 the range is 1527-1608 nm; at the angle of 45^0 the range is 1514-1597 nm; at the angle of 60^0 the range is 1501-1585 nm, at the range of 75^0 the range is 1492-1576 nm and at the angle of 89^0 the range is 1488-1573 nm. The reflectance range for TM mode is 1540-1620 nm at normal incidence; at the angle of 15^0 the range is 1537-1616 nm; at the angle of 30^0 the range is 1529-1605 nm; at the angle of 45^0 the range is 1518-1589 nm, at the angle of 60^0 the range is 1508-1574 nm, at the angle of 75^0 the range is 1500-1562 nm; and at the angle of 89^0 the range is 1497-1558 nm. Hence the total omni- direction range for this multilayer structure is lies between 1540–1558 nm and the width of the omni- direction range is 61 nm. The 1550 nm wavelength primarily used in optical communication falls in this wavelength range. Hence, we can use such a multilayered one-dimensional structure can be used as an omni-directional mirror in devices of optical communication.

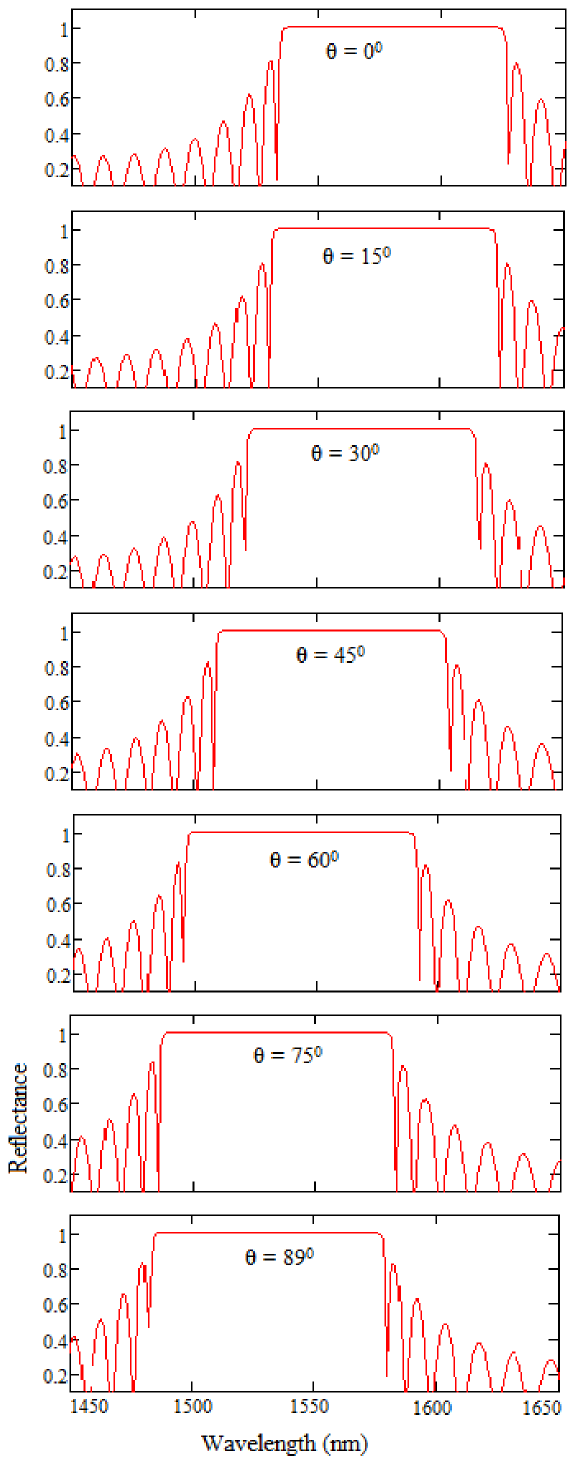

Fig. 2 Reflectance curve Vs wavelength (nm) of Ge/ZnS multilayer structure for TE mode at different angle.

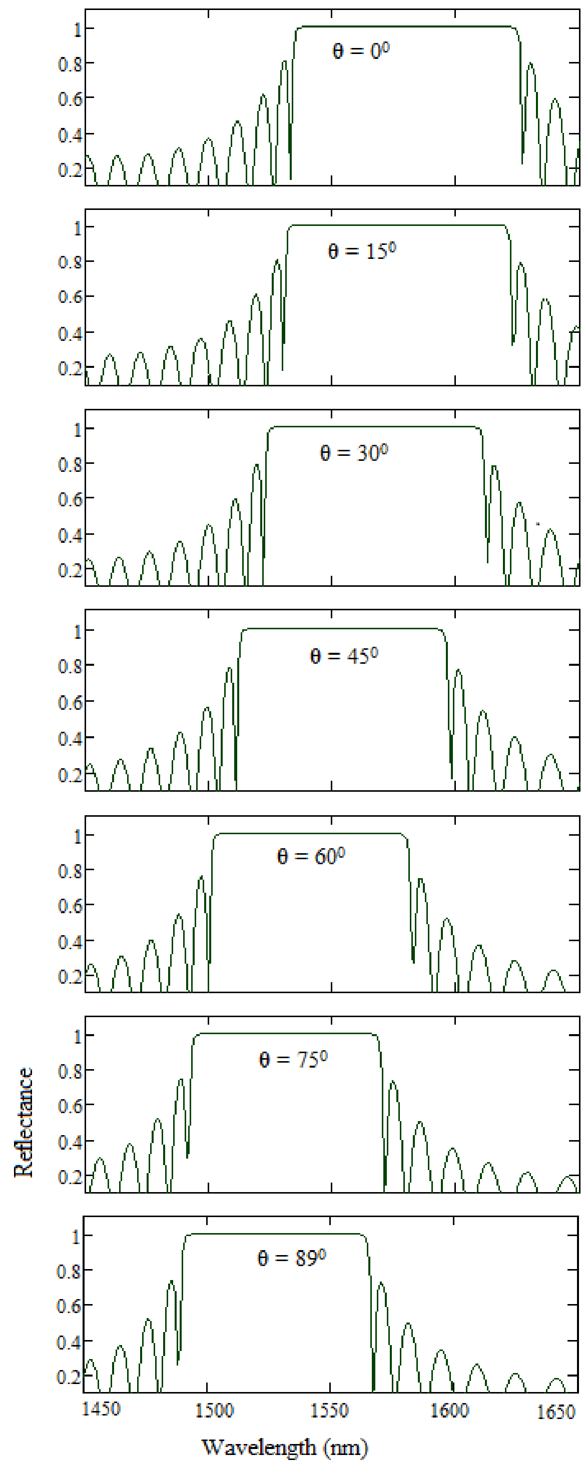

Fig. 3 Reflectance curve Vs wavelength (nm) of Ge/ZnS multilayer structure for TM mode at different angle.

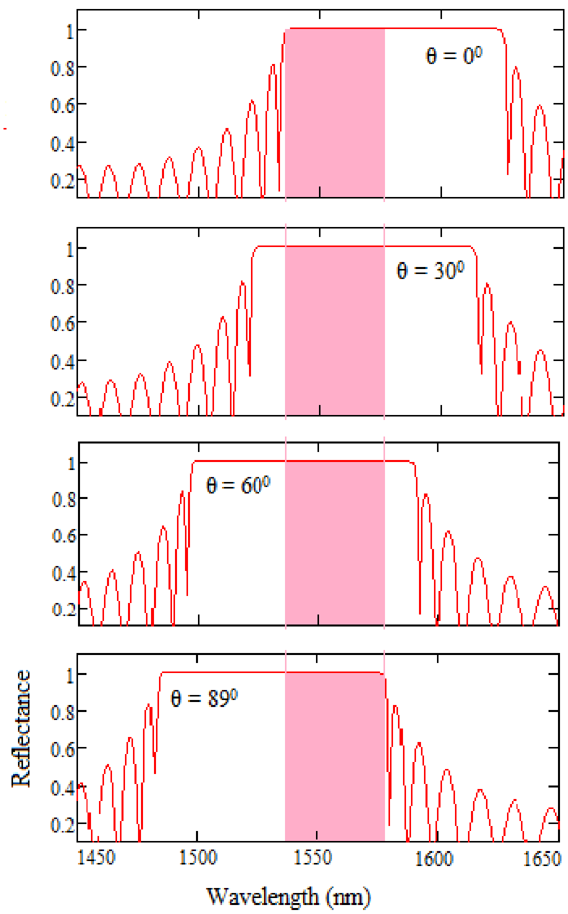

Fig. 4 Omnidirectional band gap of Ge/ZnS multilayer structure for TE mode at different ange.

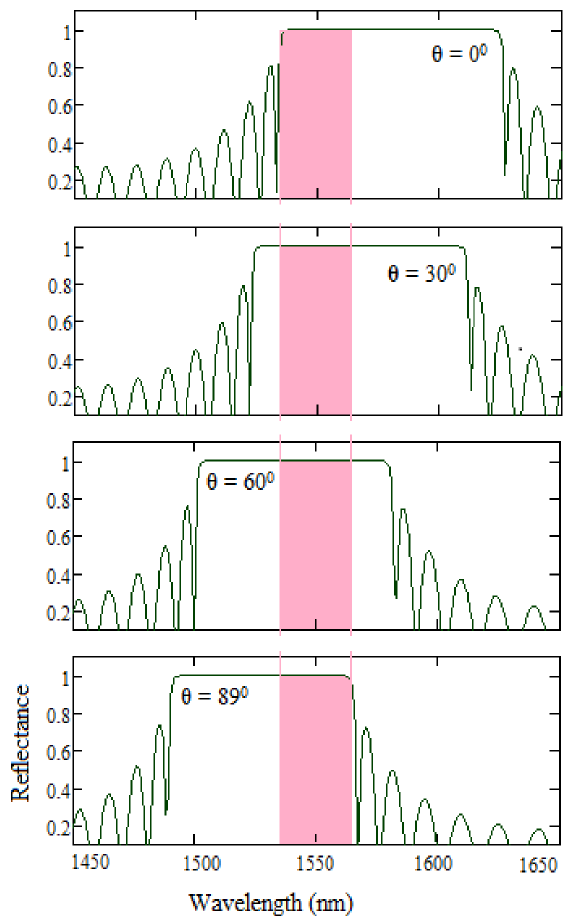

Fig. 5 Omnidirectional band gap of Ge/ZnS multilayer structure for TM mode at different ange.

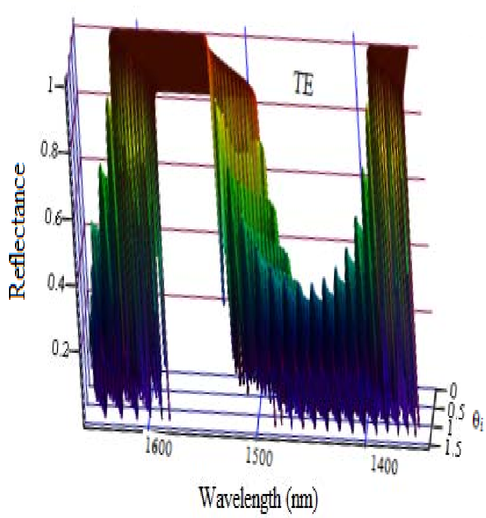

Fig. 6 Reflectance spectra of Ge/ZnS PBG for TE polarization.

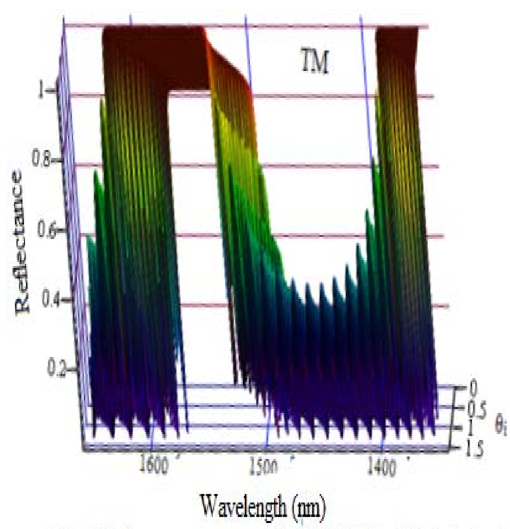

Fig. 7 Reflectance spectra of Ge/ZnS PBG for TM polarization.

Table-1: Photonic band gap for $n_1 = 4.23$, $n_2 = 2.27$, $d_1 = 0.9d$, $d_2 = 0.1d$, $d = d_1 + d_2$, N = 16 for various incident angles.

Angle of incidence (θ)	TE (nm)	Band width (nm)	TM (nm)	Band width (nm)
0	1540-1620	80	1540-1620	80
15	1536-1617	81	1537-1616	79
30	1527-1608	81	1529-1605	76
45	1514-1597	83	1518-1589	71
60	1501-1585	84	1508-1574	66
75	1492-1576	84	1500-1562	62
85	1488-1573	85	1497-1558	61

CONCLUSION

We have shown theoretically that a one-dimensional binary dielectric photonic crystal structure of Ge/ZnS can exhibit total omni-directional reflection of incident light. Such a structure can be used as a very useful optical device in the optical industry. These findings should stimulate new experiments on the implementation of such devices in optical systems.

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